Shear Behavior of Steel Fiber Reinforced Prestressed Concrete Beams

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Abstract

Prestressed concrete girders are the main superstructure elements in many bridge structures. Shear failures in these girders are undesirable due to brittle failure and little warning time. To prevent shear controlled brittle failure, it is normal practice to increase the amount of transverse reinforcement in flexural members. However, past studies have revealed that even higher transverse reinforcement ratios (i.e. > 4%) may not be able to eliminate shear failure in some cases. Moreover, the increased reinforcement makes it more difficult to place and consolidate the concrete. This research program aimed to investigate the feasibility of replacing traditional shear reinforcement in prestressed concrete beams with steel fibers. A total of 14 rectangular and 8 I-shaped prestressed concrete beams were investigated after subjecting them to a two-point loading test. The beams were cast with steel fiber ratios ranging from 0.75% to 2.00%. Experimental results revealed that the inclusion of steel fibers in concrete mix improved the shear strength of rectangular and I shaped prestressed beams. It was observed that on adding 1% fibers, the shear strength of I-beams enhanced by 23%. Moreover, in some cases, the addition of steel fibers also caused the shear failure mode to shift to flexural failure mode without traditional shear reinforcement. Furthermore, cracking behavior and ultimate strength were also improved. However, at high fiber dosages, balling of the fibers was observed and the load capacity decreased compared to beams with lower fiber contents.

Key Words: Shear failure, transverse reinforcement, pre-stressed concrete, steel fibers

1. Introduction

The versatility of concrete with respect to control on strength and conformability to any shape makes it one of the most common and popular construction materials for building structures around the world. However, concrete, being weak and brittle in tension, is prone to sudden shear failure. The most commonly adopted solution against such a failure is the provision of transverse reinforcement (shear stirrups) in concrete beams. However, past research has revealed that it is not always as effective as expected [1-3]. The use of high reinforcement ratios can also increase construction time and cost and make it difficult to work with such concrete. Furthermore, this may adversely affect the mechanical properties of concrete.

Prestressed concrete members demonstrate better flexural strength, deflection control, and particularly shear behavior than that of conventionally reinforced concrete members. On the other hand, high strength materials are generally used in prestressed concrete members, which may cause more brittle shear failures as compared to normal concrete. End zone cracking in prestressed concrete beams may also develop as a result of high prestress forces, creep and shrinkage, and thermal loadings. Therefore, well-designed shear reinforcement is provided to avoid horizontal cracks while transferring the prestress force in prestressed concrete girders. [4]

The incorporation of steel fibers in concrete has gained popularity in the bridge industry over recent decades and this trend continues to grow in other parts of the concrete industry including the construction of various types of slabs, road pavements, machine foundations, etc. One of the major advantages of SFRC is its enhanced resistance against brittle shear failure[5-7]. Steel fiber addition in concrete mixtures can enhance the shear strength of structural elements through improving the concrete cracking behavior and dowel resisting action provided by fibers [8,9]. Furthermore, the substitution of conventional shear stirrups with steel fiber reinforcement improves the behavior of structural members in terms of energy dissipation and ductility [10].

Several studies have reported that the addition of steel fibers in concrete significantly improves the cracking behavior of beams and girders by increasing the shear capacity [11-17]. It was also found that, in the absence of web reinforcement, steel fibers, in addition to enhancing the shear strength, also helped in shifting the failure mode from shear to flexure that shows the potential of steel fibers to replace traditional shear reinforcement. Steel fibers resist and redistribute stresses by bridging the diagonal tension cracks which in turn improves the shear strength and post cracking behavior of concrete members.

In this study, the shear behavior of steel fiber reinforced prestressed concrete (SFRPC) beams was investigated. Twenty-two specimens were cast and tested with varying fiber dosages. This study reports the feasibility of replacing the conventional shear stirrups (transverse reinforcement) with steel fibers in prestressed concrete beams and girders, specially constructed by precast industry.

2. Research significance and objectives

A lot of research work has been carried out exploring the possibility of incorporation of steel fibers in concrete beams to enhance its shear strength. Yet, very limited data is available on the investigation of the effect of steel fiber incorporation in prestressed reinforced concrete beams and girders. Hence, this study focuses on the feasibility of replacing conventional shear stirrups with steel fibers in prestressed rectangular and I-shaped beams. The complete replacement of shear reinforcement with steel fibers can reduce the costly manufacturing of conventional shear reinforcement leading to reductions in costs. Additionally, it will shift the failure mode from brittle-shear to flexure. This research work is mainly aimed to optimize the steel fiber dosage that can be used to partially or completely replace the conventional shear stirrups leading to improved shear behavior.

3. Experimental program and methodology

3.1 Materials

Concrete with fc’ equal to 42MPa was used in this research work. The mixture of ingredients and proportions used for casting the beams have been given in Table 1. The steel fibers have been cut from hard stainless-steel wire of 1035 MPa strength. The length of the fibers was kept 18mm while the diameter was 0.3mm. Plasticizer was also added in the mix to enhance the workability of concrete without any additional water.

High strength low relaxation steel wire was used for providing prestressing effect. The diameter of the wire used was 5.3 mm. A uniaxial tension test on these steel wires was performed to investigate its yield and ultimate strengths as mentioned in Table 2. Before placing the prestressing wires inside the specimen's mold, it was ensured that the wires should be rust free and oiled properly using kerosene oil which was then evaporated. Finally, the wired were again cleaned before using for prestressing in concrete.

3.2 Test specimens

The testing program included fourteen rectangular prestressed concrete beams and eight prestressed concrete I-girders. The rectangular beams had a cross-sectional size of 75 × 150 mm, and prestressed concrete I-girders had a height of 305mm (12 in), flange width of 125mm (5 in), and web width of 55mm (2.25in). The length of each beam was 1.37m (4.5 ft), while the span length

Table 1: Concrete mixture composition for beam specimens

Materials	Quantity
Portland cement	550 kg
Aggregate (Passing 3/4" and retained on 3/8" sieve)	583 kg
Aggregate (Passing 3/8" and retained on No. 8 sieve)	388 kg
Sand (FM = 2.6, density = 1400 kg/m^3)	658 kg
Water	200 liter
Admixture: Sikament NP-110	12.2*
Steel fibers	**

* admixture in ml/kg of cement; FM = fineness modulus
** steel fiber dosage in percentage by volume of concrete

Table 2: Tension test on steel tendons

Specimens	Specimen type	Stress (MPa)	
		Yield	Ultimate
1	High tensile wire	1260	1482
2	High tensile wire	1280	1505
3	High tensile wire	1280	1505
	Average	1273	1497

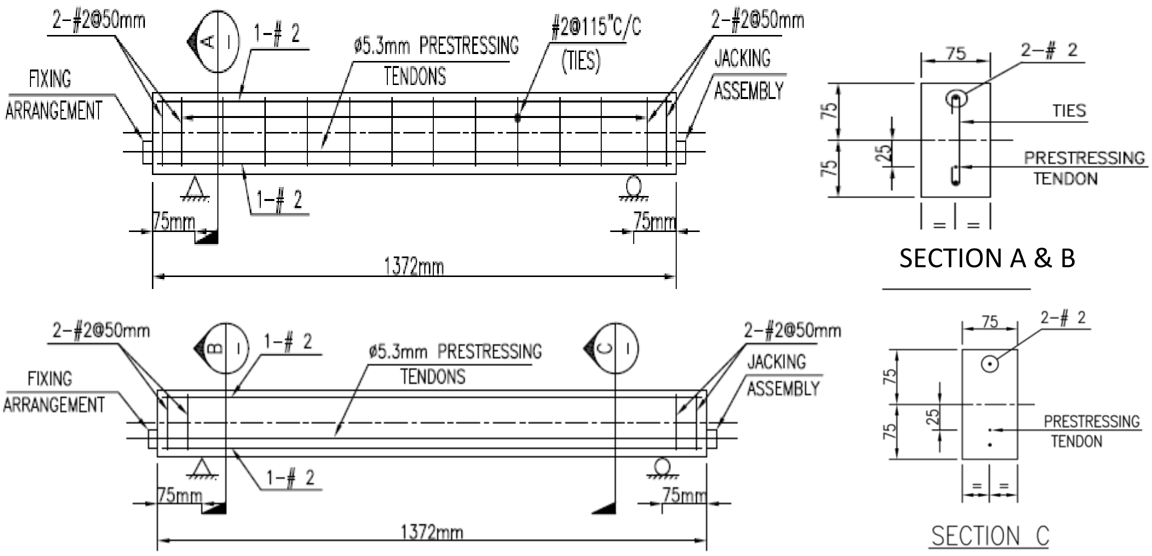
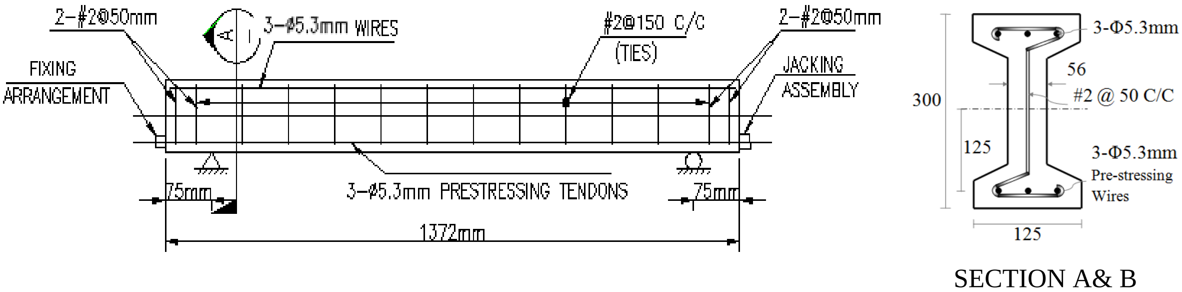
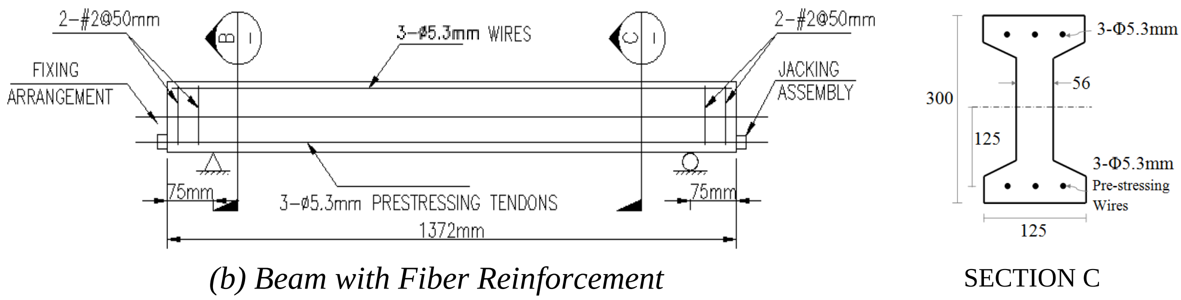


Fig. 1: Rectangular beam details



(a) Beam with Traditional Shear Stirrups



(b) Beam with Fiber Reinforcement

Fig. 2: I-beam details

used for testing was 1.22m (4 ft). The test specimen details are shown in Fig.1and Fig. 2.

Two control beams were fabricated for each cross-section type, with conventional shear reinforcement in the form of #2 single leg or double leg stirrups at a spacing of 150 mm, while the remaining beams were cast with the inclusion of steel fibers as a complete replacement of the conventional shear reinforcement. The only variable parameter in this study was fiber content, which ranged from 0.75% to 2.0%; all other parameters were kept fixed.

Two specimens for each fiber content were tested. Two stirrups were provided in each specimen at both ends, to avoid end zone cracking due to the prestressing force. Table 3 shows the test matrix. The following beam designation is used: R-#.## or I-#.##, where “R” or “I” refers to the cross-sectional shape and"#.##" represents the steel fiber dosage.

Molds made up of steel were used to cast the beams. End plates with holes were utilized to allow the prestressing steel to pass through. All joints were sealed properly using gypsum and water mixture. Before pouring the concrete, oil was applied to the inner surfaces of the molds so that de-molding could be done easily. A single prestressing wire with constant eccentricity was used in the rectangular beams, while the I-beams were prestressed with three 5.3mm diameter, low relaxation pre-stressing wires having ultimate strength of 1725 MPa. First, the prestressing strands were aligned within the forms and kept in position using grips loosely fixed on both ends of the prestressing bed. Then prestressing was carried out with a hydraulic jack against the bed end, with a prestressing force of 23 kN and 25 kN per tendon for the rectangular and I-shaped beam, respectively. After mixing, concrete was transported to the prestressing bed and placed in the formwork. Various stages of specimen preparation have been shown in Fig. 3.

a. Casting Bed with Steel Wires

b. Prestressing of Wires with Jack

c. Pouring of Concrete

d. Compaction of Concrete

e. Cutting of Prestressing Wire

f. Specimen Ready for Testing

Fig. 3: Stages of Specimen Preparation

Table 3: Test matrix

Specimen	Shape	Stirrups	Fiber volume (%)	Number of specimens
R-0.00	Rectangular	#2 @ 115mm c/c	0.00	2
R-0.75	Rectangular	-	0.75	2
R-1.00	Rectangular	-	1.00	2
R-1.25	Rectangular	-	1.25	2
R-1.50	Rectangular	-	1.50	2
R-1.75	Rectangular	-	1.75	2
R-2.00	Rectangular	-	2.00	2
I-0.00	I-shaped	#2 @ 115mm c/c	0.00	2
I-1.00	I-shaped	--	1.00	2
I-1.25	I-shaped	--	1.25	2
I-1.50	I-shaped	--	1.50	2

The prestressing wires used in all types of specimens were cut after 7 to 10 days of casting. After de-molding, the curing process was carried out using jute bags which were damped and further sealed using plastic sheets (to avoid evaporation of water). Six cylinders for each concrete mixture incorporating various fiber dosages were cast and cured together with the beam specimens to determine their compressive strength at 28 days.

3.3 Experimental test setup

The beams were kept as simply supported and tested under two-point loading arrangements (Fig. 4 and Fig.5). Deflection gauge was installed at the bottom mid-span of each beam specimen for measuring mid-span deflection. Strain gauges were attached to the prestressing tendon and concrete top surface at the mid-span. A displacement-controlled load was applied at a rate of 1mm/min using a load cell actuator with a maximum capacity of 500 kN. All specimens were loaded until their flexural or shear strength was exhausted. The crushing of concrete in the compression zone along with increased mid-span deflection was considered as the failure point. At that point, a significant reduction in load carrying capacity with wide cracks was observed. Beam specimens were painted white for better visualization of cracking pattern. Mid-span deflection, steel, and concrete strains were recorded simultaneously at a rate of 1 *Hz*.

4. Results and discussion

4.1 Concrete compressive strength

Concrete compressive strengths with various steel fiber contents are shown in Fig. 6. The compressive strength of all the mixes was above 42 MPa. The concrete compressive strength increased with the increase in fiber content. For example, with the addition of 1.25% fibers in the concrete mix, 10% increase in compressive strength is observed. This increase is mainly attributed to homogeneously distributed fibers that limit the axial and lateral expansion by restricting the crack development and internal material deterioration due to the absorbing effect of the developed stresses at the tip of the steel fibers [18,19].

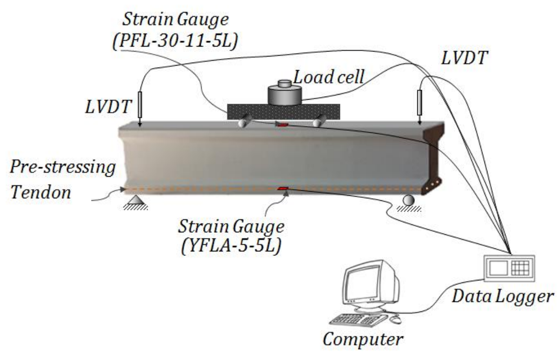


Fig. 4: Schematics of Test Setup

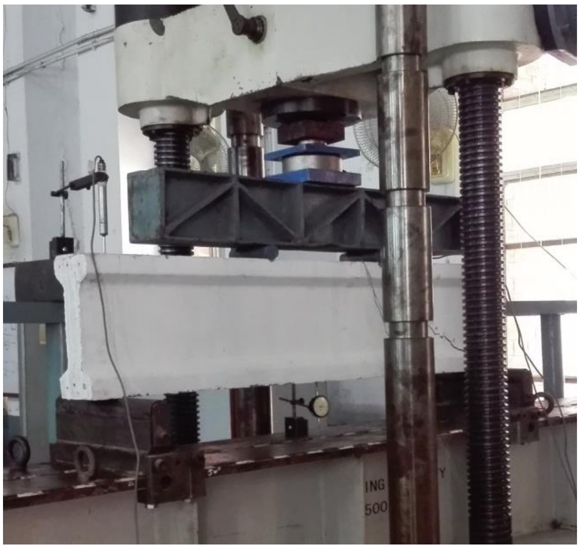


Fig. 5: Test Setup

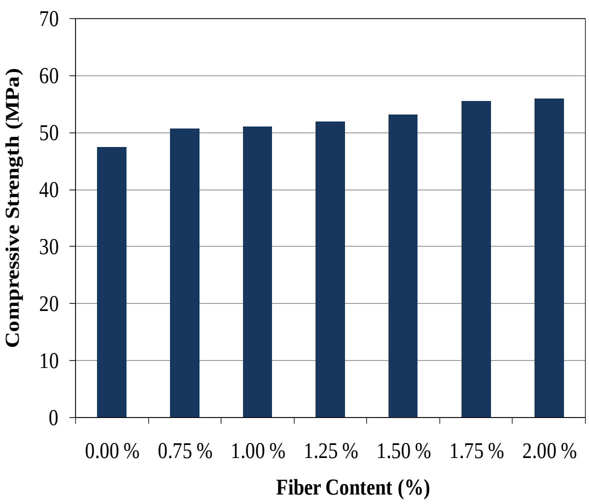
A maximum compressive strength increase of around 18% was observed for the mixture incorporating 2.0% fiber content. However, the compressive strength difference between mixtures incorporating 1.75% and 2.00% steel fibers was less than 1%, indicating that the increase in fiber content beyond 1.75% volume does not significantly contribute to increasing concrete compressive strength.

The concrete specimen without any fibers failed by the opening of a single large crack and splitting into different parts indicating the brittle mode of failure; however, cylinders incorporating steel fibers showed no concrete de-attachment or chipping off due to bridging action of steel fibers which restricted the crack propagation by stress redistribution. The failure patterns of concrete specimens with no steel fibers and 2.0% steel fibers are presented in Fig.6.

4.2 Load-deflection behavior

The load-deflection curves of the rectangular beam specimens are presented in Fig.7a. The shape of the curves at the initial stage of all the tests was almost the same regardless of the fiber content used in the specimens. This indicated that the initial stiffness is not significantly affected by the addition of fibers. It was observed that the maximum load carried by the beam specimens incorporating 0.75% steel fibers (R-0.75) was lower than that of the control specimen (R-0.00), showing that the addition of 0.75% fibers by volume was insufficient for providing similar shear strength as conventional stirrups. However, with the addition of 1.00% fibers (R-1.00) the load-deflection curve of the specimens becomes similar to the that of control specimen which indicates that by the addition of 1.00% fibers behavior similar to the control specimen can be achieved.

By further increasing the amount of steel fibers, further improvement in the behavior of test specimens is observed with a maximum of 1.75% fibers. Fiber contents greater than 1.75% resulted in strengths slightly larger than that of the control specimens but lower than that of the other fiber fractions. This may be attributed to the balling effect of steel fibers at high dosages leading to the formation of weak spots inside the beam specimens and hence, affected the strength properties.



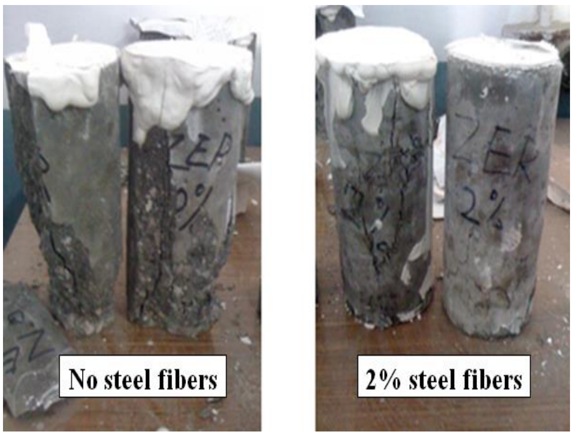
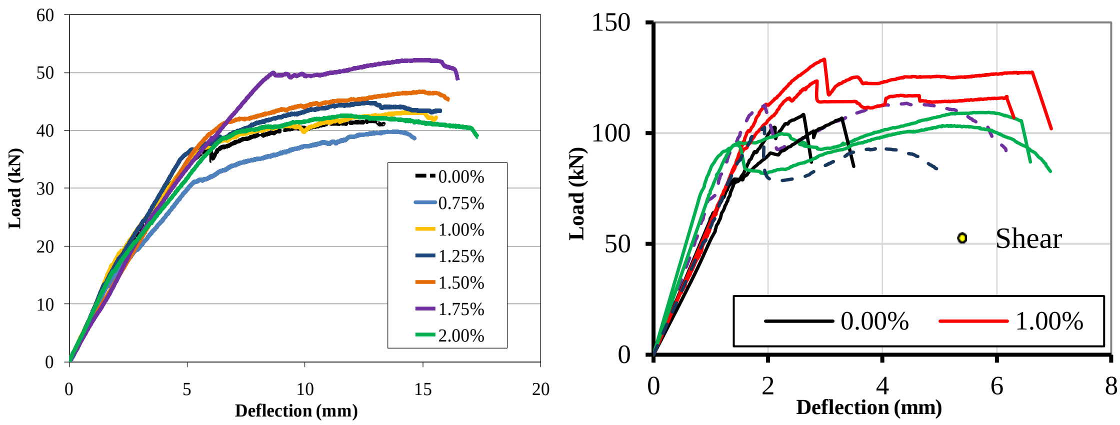


Fig. 6: Compressive strength behavior of concrete mixtures incorporating various dosages steel fibers



(a) (b)

Fig. 7: Load-deflection curves of beams with different dosages of steel

Fig. 7b. presents the load-deflection response of the I-shaped beams. The maximum increase in cracking load and the ultimate load was 12% and 23% for beams containing 1% fiber content (I-1.00). No further increase in strength was observed with more than 1% fiber content; in fact, a reduction in maximum load capacity was observed for higher fiber volume fractions (I-1.25 and I-1.50). This may be attributed to the balling of the fibers reducing consolidation and creating weak zones in the concrete.

Further, shear span to effective depth ratio, a/d, for the I-shaped specimens was 1.5, falling under the category of short shear spans (i.e. deep beam). For short shear spans, redistribution of stresses takes place after the development of inclined cracks and beam action changes to arch action to carry the extra load. Although flexural cracks appeared at the beginning the final failure was due to diagonal shear cracks.

The nominal shear capacity of the prestressed beams was also calculated according to expressions suggested by ACI 318-14, [20]:

$$V_n = V_c + V_s \quad (1)$$

Where V_c and V_s are the nominal shear strengths provided by concrete and web reinforcement respectively.

For prestressed members, V_c is smaller of V_{ci} and V_{cw}:

$$V_{ci} = 0.6\lambda\sqrt{f'_c}\,b_w d_p + V_d + \frac{V_i\,M_{cre}}{M_{max}} \quad (2)$$

$$V_{cw} = (3.5\lambda\sqrt{f'_c} + 0.3\,f_{pc})\,b_w d_p + V_p \quad (3)$$

$$V_s = \frac{A_v f_{yt} d}{s} \quad (4)$$

For non-prestressed SFRC beams, the following equation was proposed in Ref.[21] by assuming bond stress (τ) and a vertical projection of the diagonal crack equal to 0.9d, in which case the shear contribution of the fibers, V_{fr}, replaces the term V_s in the previous equations:

$$\tau = 0.68\sqrt{f'_c} \quad (5)$$

$$V_{fr} = 0.25F\sqrt{f'_c}\ \text{(MPa)} \quad (6)$$

Table 4 shows the comparison of theoretical and experimental results. The difference between analytical and experimental values is small for high fiber dosages but the disagreement for low fiber dosages is large.

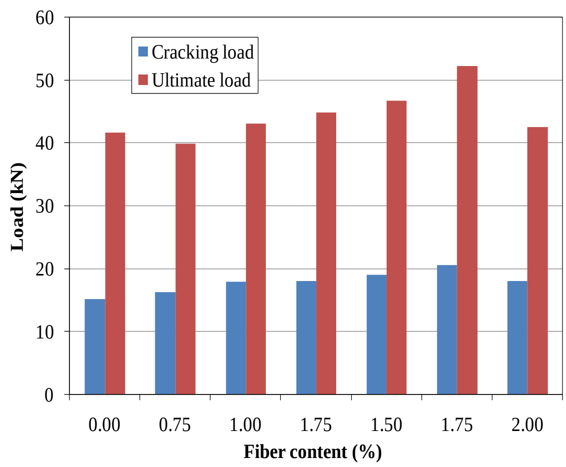


Fig. 8: Effect of fiber content on ultimate and cracking load for rectangular beams

Table 4: Shear capacity predictions

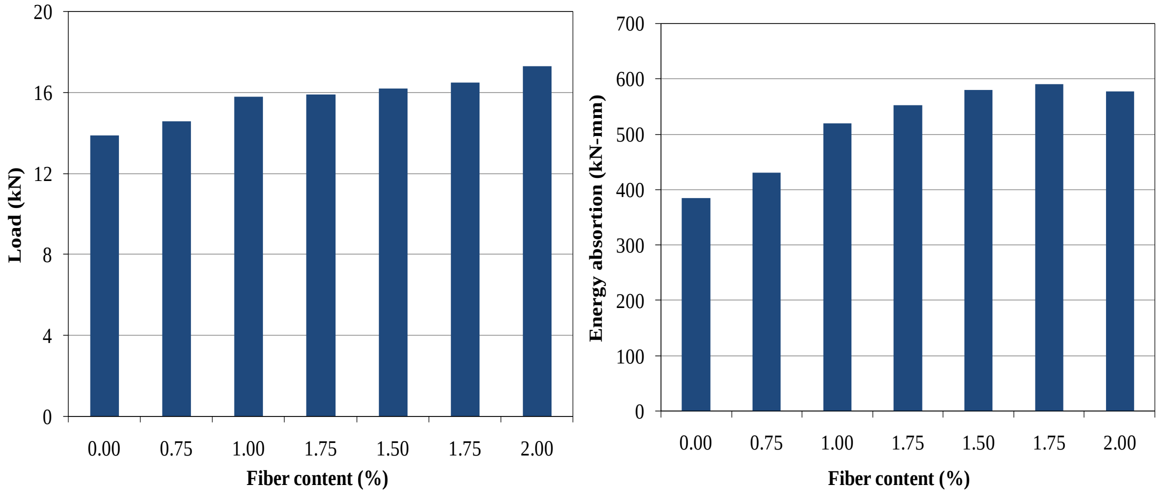
Fiber Content	V_n (kN)		% diff.
	Analytical Value	**Average Experimental Value**	
Control	54.9	54.1	2
1.00%	49.4	66.6	35
1.25%	51	56.8	11
1.50%	52.7	54.7	4

4.3 Cracking

The cracking load is identified on the load-deflection curve as the point where the initial slope of the curve is changed indicating that the concrete tensile capacity is exhausted, and the cracks have initiated. Fig.8 shows the loads corresponding to the first crack and ultimate stage of rectangular beams respectively. In general, with the increase in steel fiber content both cracking and ultimate loads were increased with a maximum of 35% and 25% respectively for 1.75% fiber dosage. It was observed that at 0.75% fiber content (R-0.75), the first cracking load was higher compared to that of the control specimen. This increased cracking strength was mainly due to lower inner material disturbance and the crack bridging effect of steel fibers. However, the ultimate load for beam specimens incorporating 0.75% fiber content was lower than that of the control specimen, indicating that the dosage less than or equal to 0.75% cannot be used as a complete replacement for traditional shear stirrups reinforcement. Furthermore, the specimen with 2% dosage of fibers exhibited smaller first crack and ultimate loads as compared to that of 1.75% (R-1.75) dosage specimen.

4.4 Mid-span deflection at failure

Fig. 9a shows mid-span deflection at failure for the rectangular beams. It was observed that the midspan deflection at failure increased with the increase in fiber content. For instance, for beams with 1.75% fibers (R-1.75), an 18% increase in mid-span deflection at failure was observed compared to that of the control specimen (R-0.00), depicting a more ductile behavior. Even though the peak load of the specimens with 2.0% steel fibers (R-2.00) was decreased due to the balling effect, the mid-span deflection at failure was nonetheless increased to 23% compared to the control specimen. It is also noteworthy that even the specimen with 0.75% fiber content (R-0.75) showed larger deflection at failure compared to the control beam specimen with stirrups (R-00). This indicates that the steel fibers strongly affect the ductility of a prestressed concrete beam even if the failure is governed by shear. Furthermore, larger failure deflection results in a longer warning time before the final collapse.



(a) (b)

Fig. 9: Mid-span deflection at ultimate load and energy absorption capacity for rectangular beams

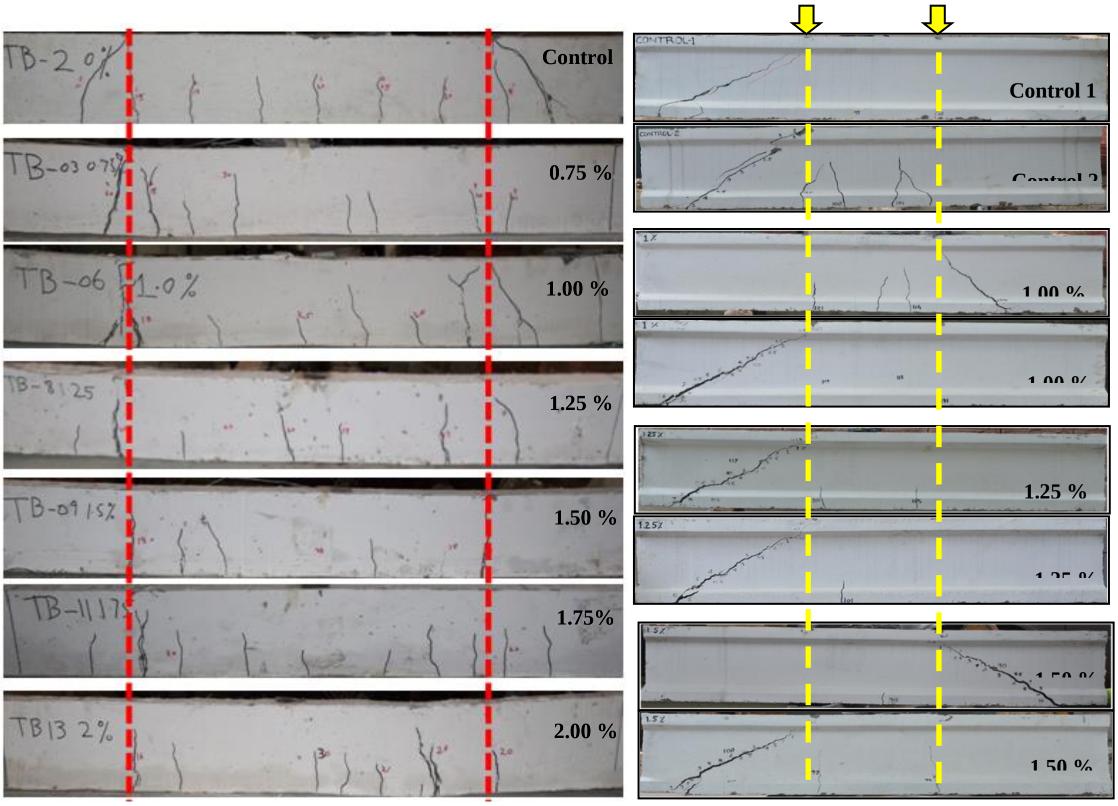


Fig. 10: Cracking patterns in tested beam specimens

4.5 Energy absorption

Energy absorbed by the beams can be determined by calculating the area under the load-deflection curve. The variation in energy absorption of rectangular prestressed beams with the change in steel fiber content is presented in Fig. 9b.The figure shows that generally, with increasing fiber content, the energy absorption of the test beam specimens is also increased. The beam with 1.75% fiber content (R-1.75) demonstrated the largest increase (53%) in the energy absorption. The increase in energy absorption and deflection at failure make SFRPC beams more suitable for active seismic regions. As energy absorption is also an indication of impact resistance of a member so steel fiber reinforced prestressed members have higher impact resistance as well.

4.6 Cracking and failure pattern

Fig. 10 shows the observed cracking pattern in all the tested beam specimens. During the initial loading stage, flexural cracks appeared in the constant moment region for all the tested beam specimens. An increased number of cracks were observed as the load was increased. In the rectangular beams, vertical cracks also developed in the shear span zone with a further increase in load, which eventually started inclining towards the loading point as the load increased. In the I-beams, which had a reduced a/d ratio, inclined cracks propagated from the supports towards the load points.

The load locations on beams are indicated by yellow lines in Fig. 10. The beams reinforced with shear stirrups without any fibers failed due to diagonal tension. By increasing the steel fiber dosage to 0.75% (R-0.75) the failure cracks shifted in the direction of the pure flexure region but still remained within the shear span. For fiber contents from 1.00% to 1.50% the failure a transition in failure mode, from diagonal tension to flexure, was observed. The failure mode shifted from diagonal tension to pure flexure when fiber content was increased to 1.75% (R-1.75). Pure flexural failure was observed at 2.00% fiber content. Therefore, it can be concluded that with steel fibers addition, the failure mode can be improved from brittle shear to ductile flexural mode.

Conversely, all the I-beams failed in diagonal tension regardless of the fiber content. This is mainly due to the smaller a/d ratio, and the reduced efficacy of steel fibers to increase the strength for these beams at higher dosages.

5. Conclusions

This study investigates the effect of steel fiber dosage on the shear behavior of prestressed reinforced concrete beams. Generally, the shear capacity of prestressed beams and mechanical properties of concrete are improved by the addition of steel fibers; however, in some cases, the strength at high fiber dosages was reduced. Further testing on large scale specimens is recommended to improve the understanding of the potential and behavior of SFRPC beams for use in construction.

The following specific conclusions can be drawn from this study:

1) An increase in fiber content from 0.0% to 2.0% in the rectangular beams gradually changed the failure mode from shear to flexure depicting a significant increase in shear strength of prestressed concrete beams. Flexural failure was observed at the fiber content of 1.75%, suggesting that fibers could be used to completely replace the conventional shear reinforcement.

2) The shear capacity of SFRPC I-beams was increased by 23% by adding 1.0% fiber content compared to the control beam. However, the mode of failure did not change, and failure ultimately occurred due to a diagonal tension crack. Nevertheless, a significant increase in ductility was observed with the addition of fibers. Increasing the fiber content above 1.0% did not result in a further increase in load capacity; conversely, a decrease in load capacity was observed at high fiber dosages which may be attributed to balling of the fibers and voids within the concrete cross-section.

3) The ductility of all the beams increased with the addition of steel fibers. The deflection at failure in the SFRPC I-beams was approximately twice that of the control beams without fibers. The energy absorption capacity was also significantly increased.

4) The ductile post-peak behavior of the SFRPC beams, even those that failed in shear, suggest that it is possible to completely replace traditional shear reinforcement with steel fibers.

5) The addition of steel fiber results in a slight increase in the compressive strength of concrete. A maximum increase of approximately 18% was witnessed for the mixture incorporating 2.00% fiber content by volume of concrete.

6) The Balling of the fibers was observed at fiber dosages above 1.0%. Therefore, higher fiber contents are not recommended without performing trial batches to evaluate the workability and consolidation characteristics of the concrete.

6. Acknowledgment

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